

# The Application of Telepresence and Virtual Reality to Subsea Exploration

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## Abstract

The operation of remote science exploration vehicles benefits greatly from the application of advanced telepresence and virtual reality operator interfaces. Telepresence, or the projection of the human sensory apparatus into a remote location, can provide scientists with a much greater intuitive understanding of the environment in which they are working than simple camera-display systems. Likewise virtual reality, or the use of highly interactive three-dimensional computer graphics, can both enhance an operator's situational awareness of an environment and also compensate (to some degree) for low bandwidth and/or long time delays in the communications channel between the operator and the vehicle. These advanced operator interfaces are important for terrestrial science and exploration applications, and are critical for missions involving the exploration of other planetary surfaces, such as on Mars. The undersea environment provides an excellent terrestrial analog to science exploration and operations on another planetary surface.

## Introduction

In the fall of 1993, NASA Ames deployed the Telepresence Remotely Operated Vehicle (TROV) under the Ross Sea ice near the McMurdo Science Station in Antarctica. The goal of the mission was to operationally test the use of

telepresence and virtual reality technology in the operator interface to the vehicle, while performing a benthic ecology study. The vehicle was operated in two modes: (1) locally, from above the dive hole through which it was launched, and (2) remotely, over a satellite communications link from a control room at the NASA Ames Research Center. Local control of the vehicle was accomplished using the Phantom control box containing joysticks and switches, with the operator viewing stereo video camera images on a stereo monitor.

Remote control of the vehicle over the satellite link was accomplished using the Virtual Environment Vehicle Interface (VEVI) control software developed at NASA Ames. The remote operator interface included either a stereo monitor (identical to that used locally) or a stereo head-mounted head-tracked display. Signals to and from the field location, including compressed video, TCP/IP data, and audio channels, were transmitted over a T1 satellite link to NASA Ames Research Center. In addition to the live stereo video from the satellite link, the operator was able to view a computer-generated graphic representation of the underwater terrain, modeled from the vehicle's sensors. This *virtual environment* contained an animated graphic model of the vehicle which reflected the state of the actual vehicle, along with ancillary information such as the vehicle track, science markers, and locations of video snapshots. The actual vehicle was driven either from

the virtual environment or through a telepresence interface. All vehicle functions could be controlled remotely over the satellite link.

## VEHICLE SYSTEMS

### Vehicle

The Telepresence Remotely Operated Vehicle (TROV) is based on a modified Phantom S2, built by Deep Ocean Engineering (San Leandro, CA). The Phantom was modified to include stereo cameras on a fast pan-tilt platform, fixed position zoom and belly cameras, fiber optic lines on the tether, SHARPS navigation transponders, and a manipulator arm. Figure 1 shows a photograph of the TROV in the underwater environment. Figure 2 shows the vehicle configuration.

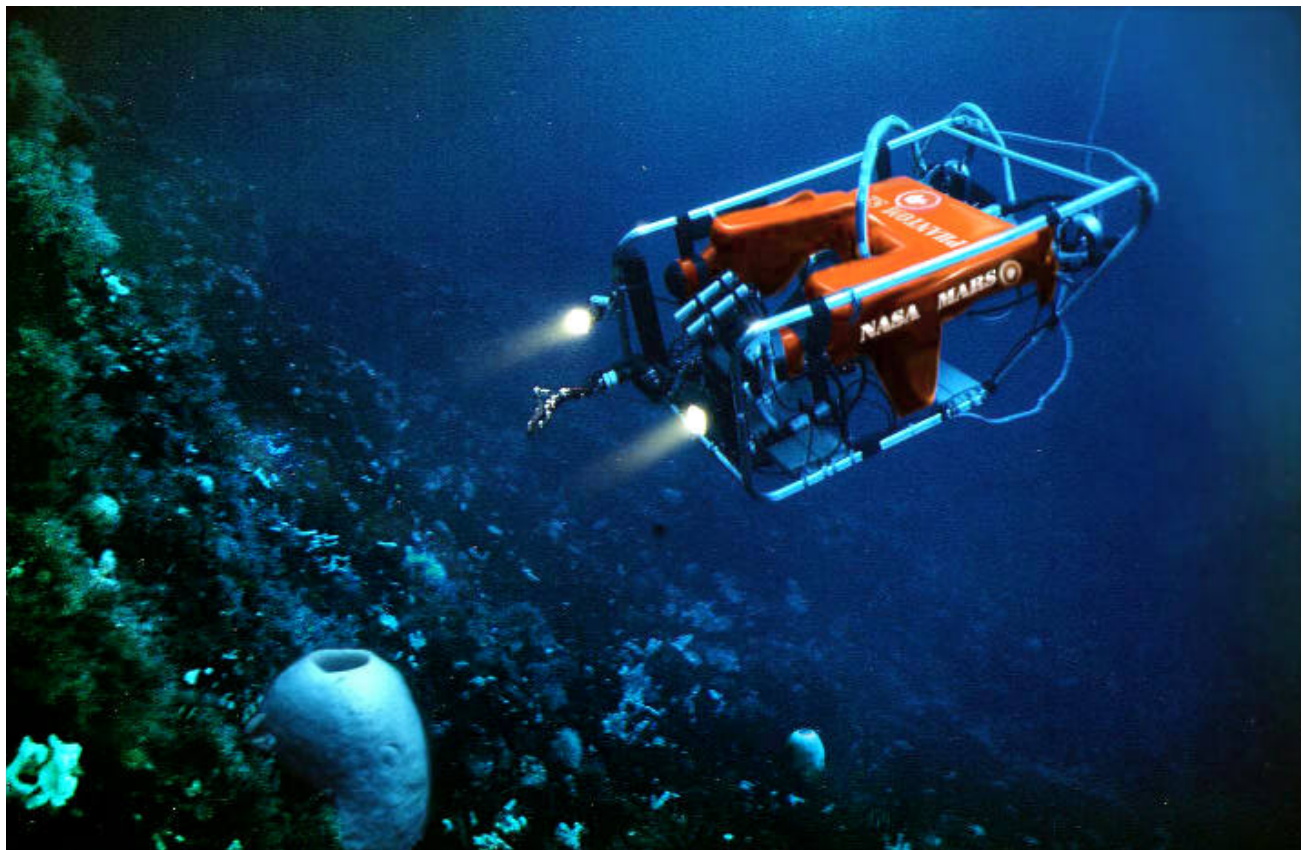
The Phantom is built around twin aluminum tubes, with a hull body of molded rigid syntactic foam that is buoyant in

water, yielding a vehicle which is nearly neutrally buoyant. The hollow tubes hold the electronics payload and the four electric thruster motors. Two thrusters are mounted horizontally, and two others are mounted at 45 degrees to vertical. Thruster control provides four degree-of-freedom motion (all three translations, plus yaw). The vehicle is incapable of commanded pitch or roll. Electrical power for thrusters and lights is supplied by wires in a 340 meter tether from the surface console

### Sensors

The primary sensor for the vehicle is a pair of stereo video cameras mounted on a rapid pan and tilt platform. The stereo cameras are mounted at approximately human interocular distance (10 cm) and can slew  $\pm 90$  degrees at rates approaching that of the human head. The system is designed to simulate human head motions, slew rates, and eye positions, which is important in operating the vehicle in a *telepresence* mode. The vehicle also carries a fixed orientation

**FIGURE 1.** The Telepresence Remotely Operated Vehicle (TROV) under the ice in the Ross Sea. The stereo cameras on the pan-tilt platform are visible at center front. The manipulator arm is to the lower right with respect to the vehicle body.

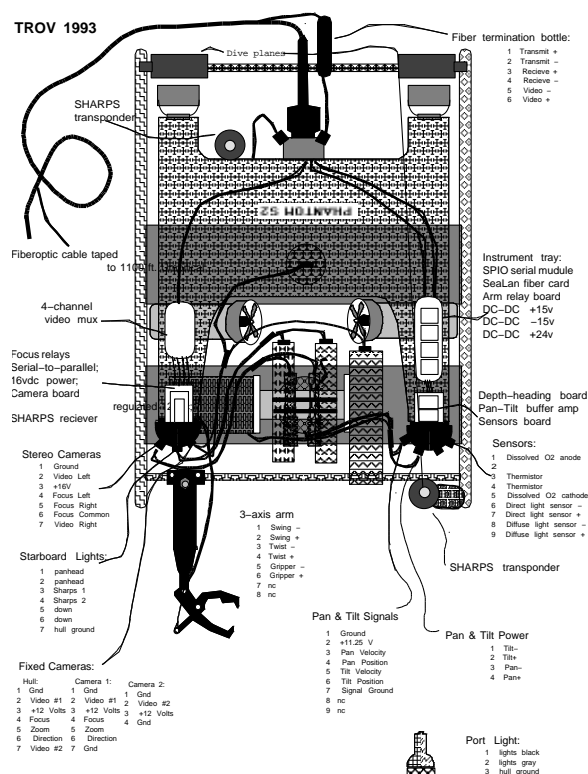


### Manipulator

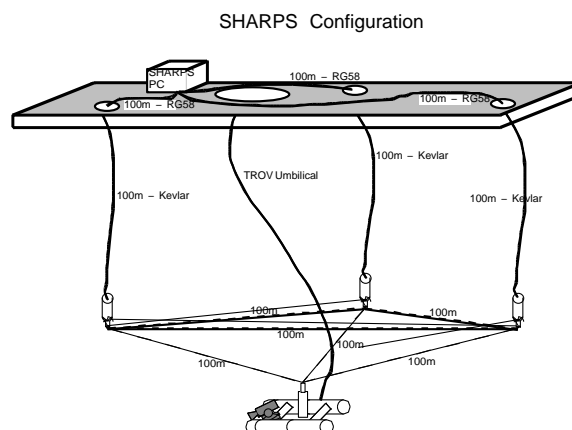
## Navigation

Localization of the TROV was achieved using a SHARPS<sup>TM</sup> Navigation System (Marquest Group). This system uses acoustic transponders to transmit and receive acoustic line-of-sight ranging signals. Two transponders were mounted on the TROV (front and rear) and three others were suspended in the water column on cables so that they formed an approximate equilateral triangle with 100 meter legs (see figure 3). The three reference transponders were connected to the control unit by coaxial cables, while the two transponders on the vehicle were driven via an RS-485 link through a twisted-pair in the main umbilical. The SHARPS system works well only when the vehicle is within 100 meters of all three transponders for triangulation.

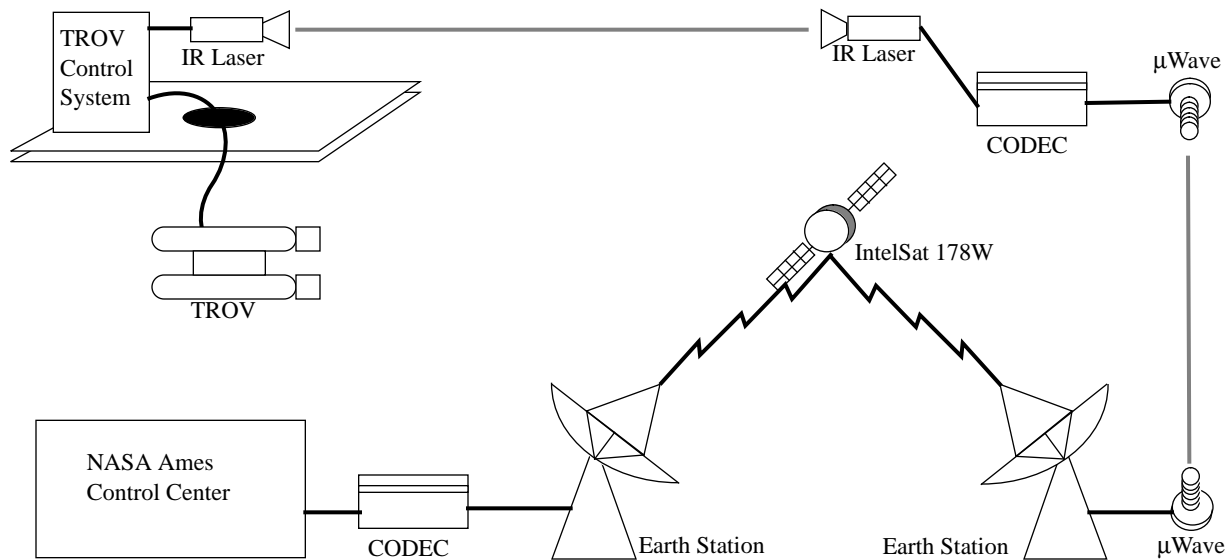
The SHARPS<sup>TM</sup> navigation system was controlled by an i386 PC. The control software provided a two-dimensional plot of the time history of the navigation track, as well as a real-time numeric display of the position. This navigation track was used by the local operators to determine the vehicle's position relative to the dive hole, as well as to determine the progress on the science transects being studied. In parallel with the live display, the navigation data were acquired by the VME control computer, and sent as telemetry over the satellite link to the Ames' control center.



**FIGURE 2.** A schematic diagram of the underwater vehicle, showing the cameras, sensors, and manipulator.



**FIGURE 3.** A Schematic for a typical deployed configuration of the SHARPS navigation equipment.



**FIGURE 4.** Schematic of the communications flow between the vehicle and NASA Ames

## Surface Controller

The surface control electronics of the Phantom S2 were augmented by a VME-based control computer with digital and analog input/output, running the VxWorks real-time operating system. The control computer was interfaced to the Phantom control box so that it provided switch closures and voltages to the control system. Local or remote operation could be selected at any time by the local operator. Remote commands over the satellite link were received through a TCP/IP connection on the VME board, and translated into control voltages or switch closures.

## Communications

Communications between the vehicle and the surface controller occurred over twisted-pairs in the ROV umbilical, augmented by a fiber optic line taped to the umbilical. The fiber optic line carried the four simultaneous video channels, while the twisted-pairs carried sensor signals and SHARPS pulses. Remote digital communications between the vehicle and NASA Ames were established using multiple links as shown in figure 4.

Live stereo video was transmitted from the location of the operations hut on the sea ice via an infrared laser to a receiver in McMurdo Station. From there, the video signal was compressed and transmitted via a microwave trans-

mitter to a satellite transmission station on Black Island, where it was retransmitted to NASA Ames over a T1 satellite channel. The compressed video portion of the T1 link used 768 Kbps, and the rest of the link was used to provide a bidirectional TCP/IP link to the vehicle control computer through which the command and telemetry signals traveled, along with bidirectional telephone service

## Architecture

The system architecture used to control this vehicle is an example of the Ames Robotic Computational Architecture (ARCA), which is a highly portable computational architecture designed at NASA Ames to provide a unified framework for integrating diverse subsystems and components for telerobotic applications.<sup>1</sup>

The architecture utilizes embedded hardware controllers, and includes single-board computers (VME-based), interface boards, and specialized processors (see Table 1). These components are used primarily for on-board vehicle processing and for synchronous tasks. VME bus was selected since it is a well established standard, has a large installed user and manufacturing base, and has a clear evolutionary path to future hardware. In addition, many VME manufacturers produce ruggedized and low power boards, which are advantageous for on-board vehicle systems.

**TABLE 1.** ARCA embedded processing hardware (VME bus based)

Type	Representative Use	Hardware
Single-board computer	Uniprocessor with multitasking	Heurikon HK68/V3D (Motorola 68030 CPU)
Interface boards	Communications & device interfacing via standard and custom protocols	Xycom XVME-400 (RS232C) Matrix MD-DAADIO (A/D, D/A, PIO) National GPIB-1014 (IEEE-488)
Specialized boards	Optimized processing for specific embedded tasks	Matrox VIP-640 (NTSC frame capture) PMC DCX-VM100 (Motor controller)

**TABLE 2.** ARCA standalone processing hardware (UNIX workstations)

Type	Representative Use	Hardware
Sun Microsystems, Inc.	UNIX applications Compute Server X Windows interfaces	SparcStation 4/370 (SPARC RISC CPU)
Silicon Graphics, Inc.	UNIX applications Compute Server Interactive 3-D graphics	4D/440 VGXT (MIPS R3000 CPU) Indigo (MIPS R4000 CPU)

Standalone processing hardware is currently a mixture of UNIX workstations as shown in Table 2. These systems are used primarily for non real-time processing, compute intensive applications, and operator interfaces. UNIX workstations provide tools, networking capability, and an environment well suited for software development. As with the embedded hardware, the systems shown in Table 2 were chosen due to large installed base and expected longevity. Silicon Graphics workstations, in particular, have shown significant improvements in recent years and provide unparalleled real-time, interactive graphics capabilities.

ARCA's standardized communications provides a system for interprocess communications and synchronization across a heterogeneous and distributed processing system. Presenting a common programming interface, standardized communications facilitates teamwork by enabling modular development and reducing the difficulty of systems integration. At this time, standardized communications is achieved via the base layer of Carnegie Mellon University's Task Control Architecture (TCA).

TCA is a distributed, layered architecture with centralized control. Communications occurs via coarse-grained message passing between modules<sup>2</sup>. The base layer of TCA implements a simple remote procedure call (RPC), in which the central control determines which module han-

dles a particular message and in what order. This RPC interface operates via Berkeley Unix TCP/IP protocols and ethernet network transmission devices.

TCA was chosen because it is capable of providing inter-process communications between processes in all ARCA processing domains and across a wide range of computing hardware. The primary limitation of TCA is that all communications are routed through the central control facility. As a result, the central process may become a bottleneck and communications will deadlock if the process execution stops. Of secondary concern is the bandwidth provided by TCP/IP. TCA's effective throughput has been estimated to be approximately 200 kilobytes per second.<sup>2</sup>

The advantages of TCA greatly outweigh its limitations. TCA provides a flexible, reliable, and easy to use communication method which greatly speeds program development. Centralized message routing facilitates the debugging of intermodule communications and coordination. Additionally, since TCA utilizes TCP/IP, it is intrinsically capable of long distance communications via the Internet. We have successfully used TCA to provide reliable communication between sites in California and France.<sup>3</sup> The impact of centralized routing and transmission bandwidth can be reduced via appropriate usage, such as limiting communications to coarse-grained message passing.

## OPERATOR INTERFACE

### Local Operator Interface

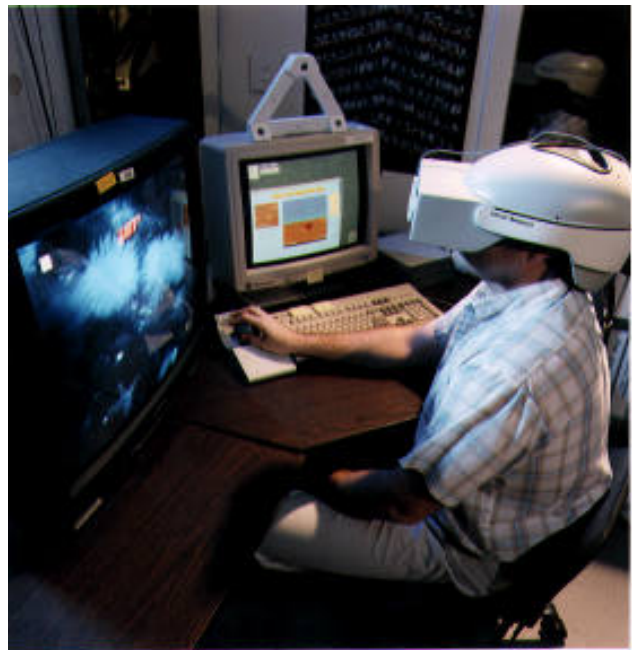
The local operator sat in a heated hut and controlled the vehicle using a modified Phantom joystick control box, while viewing stereo video camera images on a StereoGraphics™ field sequential stereo video system<sup>4</sup>. The StereoGraphics™ system uses a 120Hz scan rate to sequentially display the left and right video signals of a stereo pair at 60 Hz each. The user wears a pair of Crystal Eyes™ glasses. Each lens of the liquid crystal glasses acts as a shutter, synchronized with the images on the monitor, so that the user alternately sees the scene from one camera in each eye. The depth perception achieved with this system is excellent, especially in comparison with older systems displaying 30 Hz to each eye. Unlike earlier stereo display systems, the StereoGraphics™ system has no noticeable flicker. The observer experiences the illusion of looking through a window at the underwater scene. Other monitors displayed another camera selected by the operator, and the vehicle's track from the SHARPS navigation system.

An Amiga 2000 computer controlled the position of the pan and tilt camera platform in one of two modes: tracking the operator's head motion, or by using the mouse to position a graphic icon. The Amiga also provided a graphics overlay on the video display that included heading, depth, time, and camera position. Finally, the Amiga served for local data logging of navigation location, a time stamp, and data from other science instruments.

### Remote Operator Interface

Remote control of the vehicle over the satellite link was accomplished using the Virtual Environment Vehicle Interface (VEVI) control software developed at NASA Ames. VEVI is a modular operator interface for direct teleoperation and supervisory control of robotic vehicles. VEVI utilizes real-time interactive 3D graphics and position/orientation input devices to produce a range of operator interface modalities from flat-panel (windowed or stereoscopic) screen displays to head-mounted/head-tracking stereo displays. An operator using VEVI is shown in Figure 5. The interface provides generic vehicle control capability and has been used to control wheeled, air bearing, and underwater vehicles in a variety of environments.

VEVI executes as a loosely-synchronous process on Silicon Graphics workstations, rendering a scene with models of the controlled vehicle and the environment in which the vehicle is operating. Feedback from on-board vehicle sensors is used to update the simulated vehicle state and world model. Operators interact asynchronously with VEVI to control the graphical vehicle or to change viewing parameters (e.g., field-of-view, viewpoint). Under direct teleoperation, changes to the graphical vehicle are communicated in real-time via TCA to the actual vehicle. For supervisory control, task-level command sequences are planned within VEVI, then relayed to the vehicle controller for autonomous execution. This operating paradigm enables vehicle control in the presence of lengthy transmission delays and latencies, while increasing operator productivity and reducing fatigue.



**FIGURE 4.** An operator in a helmet-mounted display. The operator can choose either live stereo video, computer-generated graphics, or a mixture of the two, to be displayed in the helmet

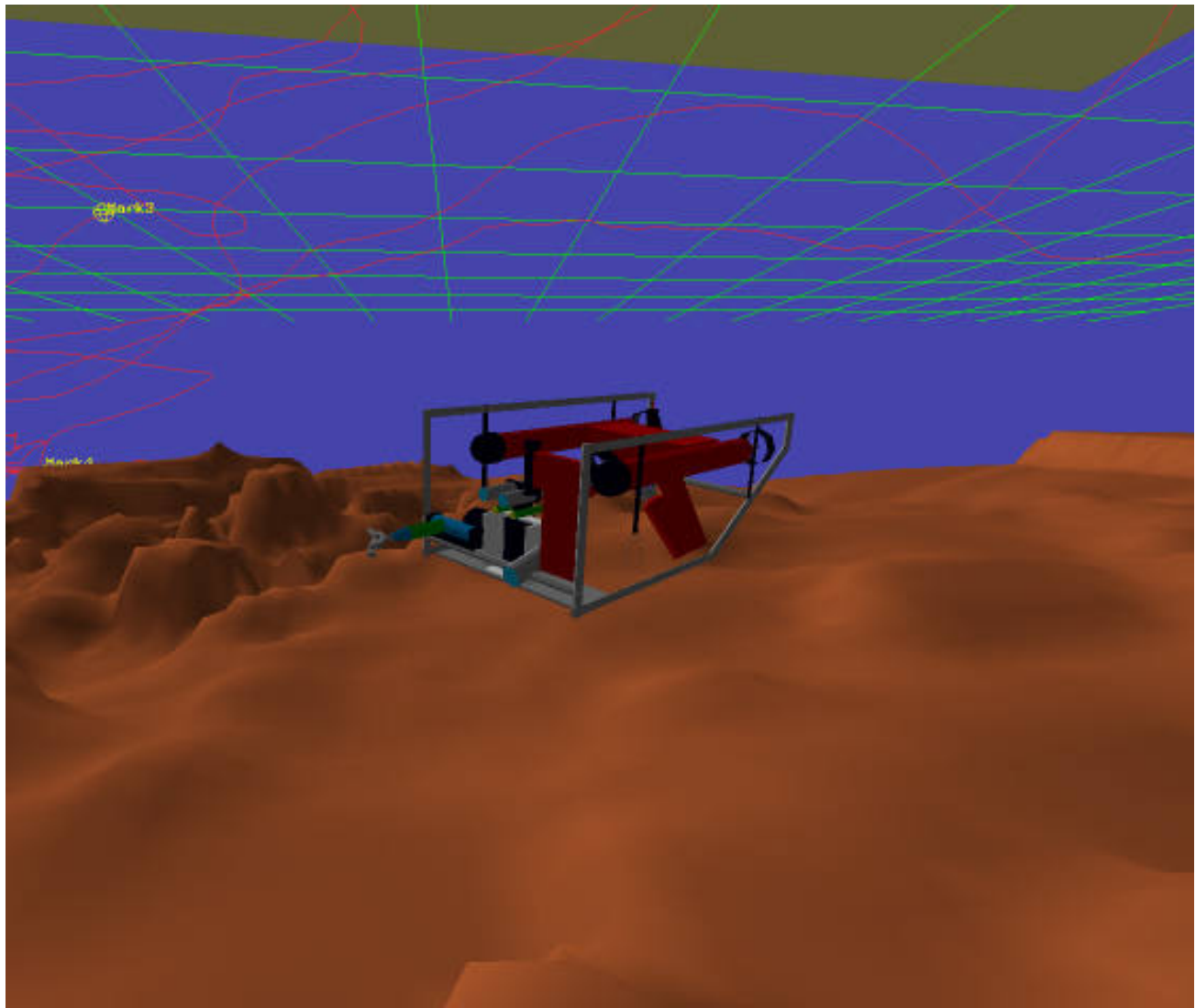
The remote operator interface included either a stereo display monitor similar to that used by the local operator, or a stereo head-mounted, head-tracked display. In addition to live stereo video, the remote operator could view a computer-generated representation of the underwater terrain, modeled from stereo images combined with navigational information, and generated off-line using a Silicon Graph-



ics workstation. This virtual environment contained an animated graphic model that reflected the state of the actual vehicle, along with ancillary information such as the vehicle navigation track, science markers, and locations of video snapshots. The vehicle could be driven either from within the virtual environment or through a live telepresence interface

The terrain models used in the virtual environment interface were generated from the on-board sensors using two techniques. One technique was to record the SHARPS position information over the telemetry link while an oper-

ator (either local or remote) drove the vehicle over the terrain at a near-constant altitude. This “ground-hugging” technique provided streams of coordinate values along the vehicle track which were interpolated onto a uniform terrain elevation map, provided the area coverage was sufficient. If the terrain coverage was sparse, then the interpolated terrain contained too many algorithmic artifacts to be useful. The second technique involved digitizing stereo camera frames, and using them to create range maps. The range maps were generated by running a Laplacian-of-Gaussian filter over the images, and then using a windowed cross-correlation technique to produce disparity values everywhere in the image at



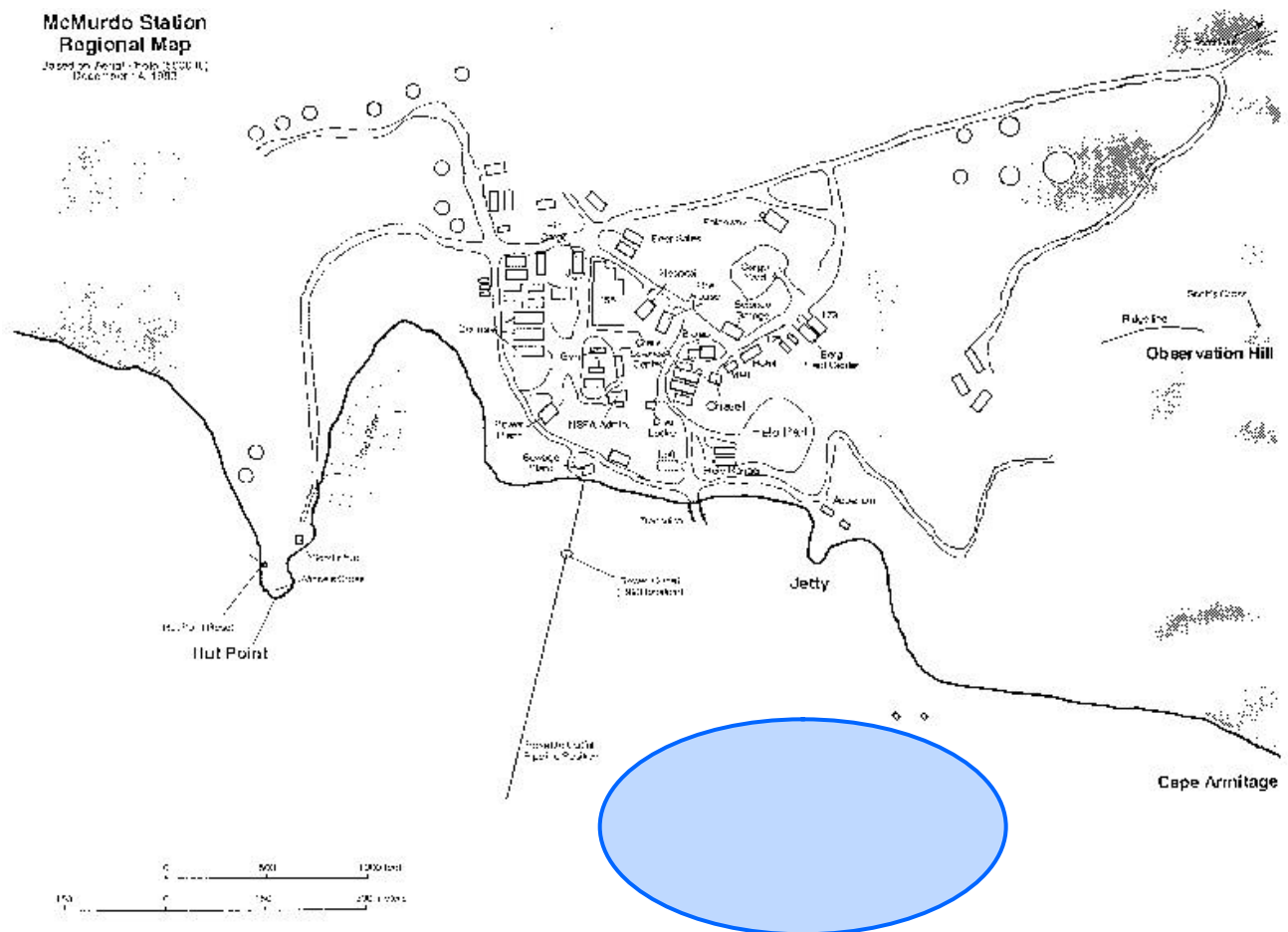
**FIGURE 6.** Screen shot of the Virtual Environment Vehicle Interface. The graphic representation of the TROV is centered in the screen. The terrain map modelled from the vehicle's sensors is shown in brown. The rectangular lines are a lat-long grid for reference

which there was sufficient contrast. These range maps, when combined with the navigation information and the pan-tilt camera angles, produced local terrain elevation values in the conical field-of-view from the current vehicle position. Multiple terrain elevation wedges generated from stereo frames taken while the vehicle moved were combined by a simple weighted average interpolation technique to produce large area uniform grid terrain elevation maps. Once the vehicle had covered an area of interest, typically 100 meters-square, the algorithms required approximately 10 minutes processor time to produce the elevation map of the area. The terrain elevation maps created with either of these techniques were input directly into the VEVI software to visualize the vehicle in the terrain (see figure 6). Once the terrain was input to the VEVI

software, the vehicle could be driven purely from within the virtual environment. The registration between the virtual terrain and the actual terrain was within an estimated 0.25 meters in areas with good coverage, which was sufficient for obstacle avoidance.

## OPERATIONS

During the 1993 Antarctic mission, TROV was operated nearly continuously for over two months locally and remotely from NASA Ames. The primary science objective of the mission was to perform transects of selected areas between 60 and 1000 feet depth, and produce a video record of the benthic organisms. A secondary objective was to perform sample collection tasks with the manipula-



**FIGURE 7.** A plan view map of the McMurdo site. The TROV operated at various points within line-of-sight of the McMurdo Station



tor arm. The data from the mission are being analyzed, and will be used to generate a multi-resolution terrain model of the area, with the video record overlaid as textured graphics on the terrain elevation data. The engineering and human performance data obtained during the mission are being used to further develop the ARCA and VEV software systems for future missions. Ultimately, we hope that this approach to science exploration missions will prove viable for use in the exploration of other planetary surfaces.

Field operations for local control of the TROV were set up in a field hut located on the McMurdo Sound sea ice. Figure 7 shows a plan view of the McMurdo Station, with the approximate area of operations highlighted with the cross-hatched oval. The hut contained a fuel-oil heater and was mounted on skis so that it could be moved from one location to another on the sea ice. Power was provided via two generators. A hatch in the floor of the hut allowed the TROV to be deployed and retrieved from inside the hut. Because all the electronic systems were located inside, most of the field operations were conducted in a "shirt-sleeve" environment. It was necessary to operate outside in the Antarctic cold only to set up and service the navigation and video transmitter systems, and to handle the TROV tether.

The field experiment represented a collaboration between a telepresence technology team from NASA Ames Research Center and two scientific research teams interested in Antarctic marine biology. The first team, interested in surveying the benthic ecology of McMurdo Sound, was headed by Dr. Jim Barry of the Monterey Bay Aquarium Research Institute (MBARI). The second team was Antarctic Science Project S022 led by Dr.'s Jim McClintock and Bill Baker. This team was interested in the chemical analysis of samples collected by the TROV.

The benthic ecology was surveyed using the TROV stereo cameras, close-up camera, and position information obtained from the navigational system. Two types of benthic surveys were performed. The first involved the re-survey of an area which had been set up for survey by divers, and had been repeatedly surveyed over the years. In this area, from a depth of 12 to 40 meters, a set of transect lines had been laid out with a stake at either end. The lines were 20 to 30 meters long. A survey along these lines involved finding the line, the stakes at each end, and then driving the TROV along the line at a constant height of about 0.5 meter off the bottom. Stereo video, with the video cameras pointed about 60 degrees below horizontal,

was recorded on Hi-8 video tape. A second video recorder was used to record the left camera only. The rate of flight was slow enough to maintain the constant height, and to visually resolve all the organisms in the field of view. After reaching the end of the transect line, the TROV turned around or went back to the start and drove over the line again, this time looking at the scene with the zoom camera zoomed in to maximum magnification. This served as a close-up lens to get detailed imaging of organisms in the field of view. Performing transects with the SHARPS system was basically similar, with the exception that a graphic display was tracked instead of a physical transect line. Approximately 30 such lines were flown in each triangular grid. Six areas were surveyed at depths ranging from 20 to 340 meters.

The manipulator arm was used to collect sample organisms and to carry a collection basket. The basket was made of PVC pipe drilled full of holes so as not to trap air, weighted and covered with netting, with a hinged door on top that could be pushed open. The basket had a handle which could be grasped by the gripper. The operator would normally place the basket on the bottom to use the gripper to gather a sample. By noting the navigation coordinates of the basket, the operator could drive around to find an interesting object, reach out with the arm and grab it with the gripper claw, return it to the basket, and insert the sample through the basket door. When the basket was full, it was grabbed in the gripper and carried to the surface ice hole. Using the joystick box and manipulator controller, this was a three-handed operation. Work is continuing to simplify the operators' interface with simple to use hand controllers, such as a data glove.

## CONCLUSIONS

Telepresence technology and virtual reality technologies provide significant advantages for benthic exploratory research, particularly for habitats where little or no preliminary information exists. Normal ROV video observations are most effective where the spatial dimensions and landscape characteristics are known by the researchers, allowing the observer to place the ROV in a spatial perspective. For unknown or poorly known environments, telepresence provides a feeling of immersion in the environment, while virtual reality provides a spatial perspective beyond the immediate ROV camera view. Thus, the observer is capable of spatial orientation in 3 dimensions for the current ROV video imagery (local spatial orientation), as well as a larger spatial scale (virtual reality). Moreover, plots of the ROV track in the virtual terrain provide a spatial 'history'

on a landscape scale. This is a distinct advantage over more conventional ROV video, where the myopia associated with a narrow field of view and lack of knowledge of the recent history of observations, makes it difficult or impossible to generate the integrated perspective that is provided by these new technologies.

Regarding the objective of obtaining estimates of the densities of the dominant benthic fauna along video transects in McMurdo Sound, the TROV was a considerable advance over conventional ROVs. The use of stereo video is potentially a breakthrough as a research tool for scientists in that it enables calculations of the spatial dimensions of video images, and thus, quantification of various parameters in the field of view (e.g. sizes of objects, distances between objects). Incorporation of high resolution navigation equipment with stereo video further enhances the quantitative nature of this system by providing highly accurate measurements of the positions of objects, distances traveled, and distances between objects.

This experiment represents a first in the use of telepresence and virtual reality for the exploration of a previously unknown scientific environment, using rendered terrain models in the environment. The use of telepresence and virtual reality for scientific exploration promises to revolutionize the study of hostile and extreme environments. By keeping human controllers actively involved, but providing better interfaces to the machines and better data visualization, better science can be achieved. The fidelity of the data record allowed by this technology, and the ease with which it can be recreated for archival study offer a significant improvement in the capabilities for data analysis. Finally, telepresence and virtual reality, both as a control system and as a data visualization method, afford the potential for distribution to a wider scientific community than would be possible with more conventional methods.

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